Intensity noise reduction in semiconductor lasers by amplitude-phase decorrelation

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Detuned operation of a laser results in coupling of field amplitude and phase fluctuations. In a semiconductor laser, this coupling is known to be very large. We demonstrate that it can be used to significantly reduce intensity noise below its intrinsic limit.

Since the first measurements by Welford and Mooradian[1] of fundamental linewidth enhancement in semiconductor lasers, a large body of research has considered the origin and implications of the linewidth enhancement parameter α.[1-3] This parameter gives a measure of amplitude-phase coupling in semiconductor lasers resulting from detuned operation. In terms of laser dynamics, the linewidth enhancement effect results from measurement of field amplitude fluctuations by the field phase. As first described by Henry,[2] amplitude fluctuations cause small transient perturbations to the active-layer carrier density which are transferred to the phase via the carrier-density dependent refractive index. Intensity noise is thus coupled to the field phase causing a phase noise (linewidth) enhancement. In this letter we show that this information stored on the field phase can be used to reduce laser intensity noise. Optimal reduction results in decorrelation of field amplitude and phase fluctuations. After discussing the effect theoretically, we demonstrate reduction of intrinsic laser intensity noise. We also show that the strength of this effect is diminished at higher bias levels by an additional component of laser linewidth not described by the modified Schawlow–Townes equation. This extra component is observed in all semiconductor laser structures (its origin, however, probably varies) including those studied here.

For the purpose of this analysis we will restrict attention to fluctuation frequencies less than the population relaxation rate (i.e., $\Omega < 1/\tau_R$ where τ_R is the relaxation oscillation damping time). This allows the population to be eliminated from the dynamics. Small-signal equations can then be developed for the field amplitude and phase fluctuations in the standard way, leading to equations of the form

$$\dot{\rho} = -\omega_R^2 \tau_R \rho + \Delta_R, \tag{1}$$

$$\dot{\phi} = \alpha \omega_R^2 \tau_R \rho + \Delta_I + \Delta_0, \tag{2}$$

where ρ is a small-signal field-amplitude fluctuation, $\dot{\phi}$ is a small-signal instantaneous-frequency deviation, and ω_R^2 is the relaxation oscillation frequency. Other quantities appearing above are the two quadrature parts (Δ_R and Δ_I) of the Langevin fluctuation term accounting for spontaneous emission into the lasing mode.[2,3] Note that α appears in Eq. (2) and has a typical value between -2 and -6 in bulk semiconductor active layers. α depends on the amount of gain spectrum detuning. In a semiconductor laser strong detuning effects occur at the gain maximum owing to band-filling effects.[3] Finally, we have added a phenomenological Langevin source to Eq. (2) to account for the non-Schawlow–Townes linewidth mentioned earlier. The dynamics leading to this extra linewidth component are undoubtedly more complicated than modeled here, however, the presence of this term (which is assumed to be uncorrelated with the other noise sources) serves to illustrate in a simple way the effect of the additional component of linewidth on our measurement.

By solving Eqs. (1) and (2) and using calculated normalizations for the Langevin fluctuation sources, it can be shown that the fundamental, quantum-limited linewidth of a semiconductor laser is given by the equation:[2,3]

$$\Delta\omega = \Delta\omega_{ST}(1+\alpha^2) + \Delta\omega_0 \tag{3a}$$

$$\Delta\omega_{ST} = S/2P, \tag{3b}$$

where $\Delta\omega_{ST}$ is the Schawlow–Townes linewidth and $\Delta\omega_0$ is the extra linewidth component (note, mathematically, $\Delta\omega_0$ is the spectral density of the source Δ_0). In addition, S is the spontaneous emission rate into the lasing mode, and P is the average number of photons in the mode. Interestingly, because α is a one-way coupling (i.e., from fluctuations in amplitude to fluctuations in phase), the laser power fluctuation spectrum is unaffected by detuning. At fluctuation frequencies less than $\omega_R^2 \tau_R$ (this is normally several GHz in conventional devices) this spectrum flattens out to a value given by[3]

$$W_I(\Omega)/I^2 = 2S/P\omega_R^4 \tau_R^2, \tag{4}$$

where I is the average total output power. At high photon levels in the lasing mode this can be shown to approach:

$$W_I(\Omega) = n_{sp} 2\hbar\omega I, \tag{5}$$

which is within a factor n_{sp} of the standard shot noise floor. The term n_{sp} is the spontaneous noise enhancement factor. In semiconductor lasers having bulk active layers n_{sp} is approximately 2.5.

The correlation between amplitude and phase fluctuations caused by the α parameter can be used to reduce intensity noise by passing the laser radiation through an optical frequency discriminator. This can be easily implemented by using a Michelson interferometer held at an intermediate transmission point. In this configuration, instantaneous frequency deviations in the input field (i.e., $\dot{\phi}$) will translate into intensity transmission variation through the Michelson. To study this effect theoretically, consider the effect of a transmission function $T(\Omega)$ on a Fourier component of the input field $\hat{E}_I(\Omega)$ at optical frequency

Ω. Provided the separation between the frequency of interest, Ω, and the lasing frequency ω is small in comparison to the frequency span between transmission peaks in the Michelson, a Taylor expansion of the transfer function about the lasing frequency is possible as shown below:

$$\hat{E}_o(\Omega) = T(\Omega)\,\hat{E}_I(\Omega)$$
$$\approx T(\omega)\,\hat{E}_I(\Omega) + T'(\omega)(\Omega - \omega)\,\hat{E}_I(\Omega), \qquad (6)$$

where $\hat{E}_o(\Omega)$ is the output field amplitude at frequency Ω and $T'(\omega)$ is the derivative of the transmission function with respect to frequency. By defining a slowly varying Fourier input field amplitude $\hat{A}_I$ as follows: $\hat{E}_I(\Omega) = \hat{A}_I(\Omega - \omega)$ and similarly for $\hat{E}_o(\Omega)$, Eq. (6) can be identified as the Fourier transform of the following equation:

$$A_o(t) = T(\omega)A_I(t) - iT'(\omega)\,\dot{A}_I(t), \qquad (7)$$

where the Fourier transform is from the slowly varying temporal space to the corresponding shifted frequency space $\Omega - \omega$. Expressing $A_I(t)$ and $A_o(t)$ in terms of corresponding small-signal amplitude and phase fluctuations, it is straightforward to compute the effect of transmission through the Michelson on the amplitude fluctuations. A simple analysis shows

$$\rho_o(t) = T_R\rho_I(t) + T'_R \cdot \dot{\phi}_I(t)$$
$$= (T_R + T'_R\alpha\omega_R^2\tau_R)\rho_I(t) + T'_R(\Delta_I + \Delta_0), \qquad (8)$$

where the second equality follows from Eq. (2) and where T_R is the real part of T. The first equality gives the intuitive result that the output from the Michelson consists of two parts: a "direct" part giving the simple amplitude transmittance through the Michelson, and an "indirect" part depending on the instantaneous frequency fluctuation of the input field relative to the lasing line center. Normally, this second component would produce only an additive uncorrelated intensity noise. As seen in the second equality in Eq. (8), however, the correlation between phase noise and amplitude noise makes possible a reduction of the intensity noise in the output field. Since α is a negative quantity, for a certain positive T'_R the term involving $\rho_I(t)$ in Eq. (8) is zero. What remains is the uncorrelated phase noise term (i.e., $\Delta_I + \Delta_0$) which, as shown below, will generally produce less intensity noise than in the original input signal. This reduction is therefore accomplished by decorrelation of the amplitude and phase fluctuations (see Fig. 1). It should also be noted here that $\dot{\phi}_{\text{out}} = \dot{\phi}_{\text{in}}$. This is easily proven using the above formalism.

It is straightforward to compute the intensity noise spectral density function output from the Michelson, W_I^{Out}, using (8) in conjunction with (1), (2), and (4). We find

$$\frac{W_I^{\text{Out}}}{I_{\text{Out}}^2} = \left[\left(1 + \frac{T'_R}{T_R}\alpha\omega_R^2\tau_R\right)^2 + \left(\frac{T'_R}{T_R}\omega_R^2\tau_R\right)^2(1+\beta)\right]\frac{W_I^{\text{In}}}{I_{\text{In}}^2}, \qquad (9)$$

where $\beta = \Delta\omega_0/\Delta\omega_{\text{ST}}$. By minimizing this function with respect to T'_R (the Michelson transmission slope), the optimum output intensity noise spectrum is given by

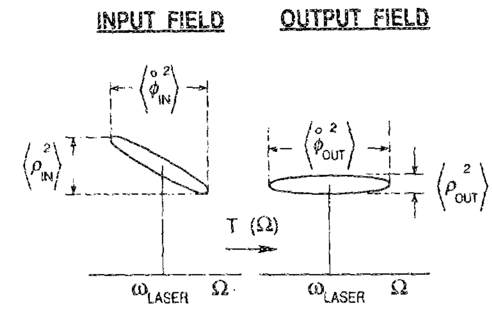

FIG. 1. Intuitive picture of decorrelation technique. Amplitude and frequency fluctuations of laser output (Michelson input) are strongly correlated (tilted fluctuation ellipse). Decorrelation by the Michelson reduces the amplitude fluctuations of the output field.

$$\frac{W_I^{\text{Out}}}{I_{\text{Out}}^2} = \frac{(1+\beta)}{(1+\alpha^2+\beta)}\frac{W_I^{\text{In}}}{I_{\text{In}}^2}. \qquad (10)$$

For $\alpha = -5$ and $\beta = 0$, this is a noise floor 26 times lower than the normal quantum noise floor. Furthermore, this reduction is predicted to be the same for all laser powers. In practice, however, β is a nonzero, increasing function of laser power since $\Delta\omega_{\text{ST}}$ varies inversely with power. Thus, for finite β, the net reduction in noise should diminish with increasing bias point.

The laser diode employed in this measurement was an Ortel research-model distributed feedback laser (DFB) operating at 1.3 μm. The device threshold current was 21.8 mA. An optical isolator with isolation of 60 dB was used. Measured linewidth versus inverse power data for this device was linear in accordance with Eq. (3a) and could be modeled using $\Delta\omega_0/2\pi = 7$ MHz and $\alpha = -2.33$. One arm of the Michelson was adjustable using a micrometer for coarse motion and a piezoelectric actuator for fine motion. The output from the Michelson was focused onto a high quantum efficiency (90%) InGaAs detector. The photocurrent noise signal was subsequently amplified by 52 dB over the frequency band 10 MHz to 1 GHz and then analyzed using a low noise spectrum analyzer. Lock-in detection was also employed to further improve the detection sensitivity. The directly detected laser intensity noise was

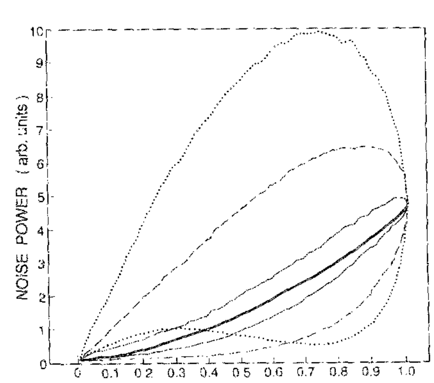

FIG. 2. Measured noise power vs normalized intensity transmission through the Michelson interferometer for optical path differences of 0, 1, 4, and 7 mm. Each loop results from piezoelectrically scanning the Michelson through one complete transmission fringe. Loop areas increase with increasing interferometer path difference.

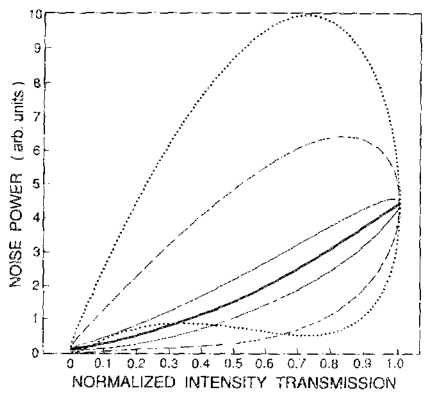

FIG. 3. Theoretical noise power vs normalized intensity transmission through the Michelson for optical path differences of 0, 1, 4, and 7 mm. Each loop results from varying the path difference minutely through one complete transmission fringe.

easily observable and exhibited the correct flat, low-frequency behavior as well as the correct dependence on laser power [i.e., decreasing noise with increasing output power at first, followed by an eventual linear increase in noise at high bias as the shot noise regime was entered, see Eqs. (4) and (5)].

Measurements were conducted by using a chart recorder to plot measured noise power (at a selected spectrum analyzer frequency and bandwidth) versus normalized intensity transmission through the Michelson (proportional to mean detector photocurrent). A single measurement would consist of scanning the Michelson piezoelectrically through one transmission fringe at a given amount of interferometer path difference. By doing this, the slope of the transmission function [i.e., T_R' in Eq. (9)] varies between negative and positive extremes of equal magnitude, which increase with increasing interferometer path difference. A set of such measurements taken at 130 MHz (an arbitrary spectrum analyzer setting-other frequencies gave similar results) is presented in Fig. 2 for varying amounts of path difference. The resulting loops increase in area as the path difference is increased. A zero path-difference loop (intrinsic noise) is also shown for comparison (note, this is a loop of zero area). The positive slope side of the transmission function produces the loop branch with noise reduction and the negative transmission slope produces the branch with noise enhancement. The laser bias was set at 23.3 mA (0.34 mW laser output power) for this measurement. The intrinsic unattenuated laser relative intensity noise (RIN) was measured to be -130 dB/Hz at this bias. For comparison we present theoretical noise-loop plots in Fig. 3 generated using Eq. (9). For these plots we have assumed $\alpha = -2.33$ and $\beta = 0.35$ (from linewidth data), and, in addition, $\tau_R \omega_R^2 =$ 34 GHz. (ω_R inferred from relaxation resonance measurement on this laser and τ_R taken from the literature[4]). The agreement is good.

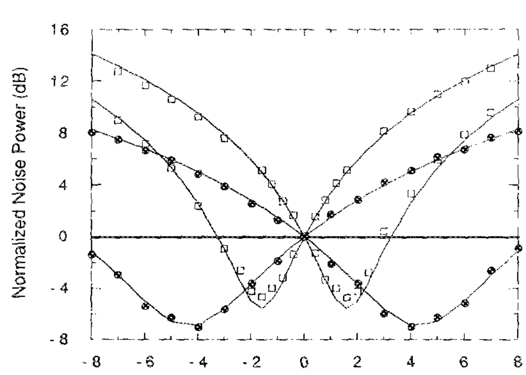

FIG. 4. Measured (points) and theoretical (solid curves) detector noise power at Michelson half-transmission point vs total optical path difference in Michelson. Noise power is plotted relative to measured noise power at zero delay and half transmission. Two laser bias levels are measured.

Cross sections of the above noise loops (both experimental and theoretical) appear in Fig. 4. These are plots of noise power at the interferometer half-transmission points versus interferometer path difference. The noise power is plotted relative to the zero path difference noise power. Both the reduced noise and enhanced noise branches are apparent. The maximum noise reduction (measured and theoretical) is 7.0 dB. Experimental and theoretical plots at a higher bias of 25.7 mA (0.83 mW) are also shown. In the theoretical plot α is unchanged from before, however, $\beta = 1.08$ is used due the measured reduction of $\Delta\omega_{ST}$. In addition, $\omega_R^2 \tau_R = 82$ GHz in accordance with the previous value and the known variation in power of this quantity. The intrinsic unattenuated RIN was measured to be -140 dB/Hz. At this higher bias level, the maximum noise reduction is predicted and measured to occur for a smaller interferometer path difference. Furthermore, as a result of the larger β at this bias, the maximum noise reduction is reduced to approximately 4.7 dB. Measurements at yet higher biases confirmed that the reduction continued to diminish.

In conclusion, we have proposed and demonstrated a new and simple method for reducing intensity noise in semiconductor lasers. The technique should be applicable in any laser system exhibiting strong gain spectrum detuning. A maximum measured intensity noise reduction of 7.0 dB was recorded for low-power operation. Reductions in the measured extra component of linewidth could enable measurable intensity noise reduction at higher power levels, potentially to noise levels below the shot noise floor. Finally, we note that the theoretical analysis presented here is based on a generic transmission function $T(\Omega)$ describing a passive linear optical system. Consequently, a Michelson interferometer is only one of many possible implementations.

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